

# Mapping Key Subsurface Boundaries to Determine Maximum Thickness of Methane Hydrate within the Blake Ridge Region of Offshore North Carolina, USA, Constrained with Three-Dimensional Seismic Data and Well Logs

Senior Research Thesis

Presented in partial fulfillment of the requirements for graduation  
with research distinction in Geological Sciences in the undergraduate colleges  
of The Ohio State University

By

Jacqueline A. Mills

December 2015

Approved by

A handwritten signature in dark ink, appearing to be 'DS' with a long horizontal stroke extending to the right, positioned above a solid horizontal line.

Derek Sawyer, Advisor  
School of Earth Sciences

## TABLE OF CONTENTS

Abstract.....	i
Dedication.....	ii
Acknowledgements.....	iii
List of Figures.....	iv
Introduction	
Hydrates.....	1
Significance of Hydrates in Energy, Climate, and Geohazards.....	2
The Geologic Setting of the Blake Ridge Region .....	3
3D Seismic Datasets and Well Logs from ODP Leg 164.....	4
Methodology	
Mapping Hydrates.....	6
Results	
3D Mapping of Hydrate System of Blake Ridge.....	8
Discussion.....	9
Conclusions.....	14
Suggestions for Future Research.....	15
Figures .....	16
References Cited.....	29

## **ABSTRACT**

My undergraduate thesis was mapping key subsurface boundaries to determine the maximum possible thickness of methane hydrate within the hydrate stability zone contained in marine sediment within the Blake Ridge region of offshore North Carolina, USA. Blake Ridge is approximately 385 miles ESE of Savannah, Georgia in water depths ranging from 1935 meters to 2513 meters. Methane hydrates are an ice with a crystalline structure consisting of interlocking water molecules surrounding a methane molecule forming in a delicate zone of low temperatures and high pressures within the Arctic permafrost or ocean sediments. Using the software packages IHS Kingdom Suite, ArcGIS, and Adobe Illustrator I analyzed three-dimensional seismic data in order to map the two key subsurface boundaries for this study: the sea floor and the bottom simulating reflector (BSR). I produced contoured structural maps and amplitude maps of each surface to correlate how to identify the BSR and at what depth it should be appearing. Comparing my results to a past study in this area, my seafloor bathymetry was similar and my BSR was also subparallel to the seafloor, however the depth of my BSR was shallower by 500 meters to 600 meters. The reason for this difference is not yet established. This general procedure has been applied in other hydrate provinces and is also applied in current mainstream oil and gas industry. Given that methane hydrates are potentially a global significant reservoir of natural gas, mapping is vital for quantifying the potential energy resource that may be extractable in the future.

To my parents, Mark R. Mills and Shelia A. Mills.

## ACKNOWLEDGEMENTS

First, I would like to thank Dr. Derek Sawyer for his help and support throughout the process of completing my thesis, and helping me with the great opportunity to defend my thesis as an undergraduate. This would not have been possible without his patience and guidance. I would also like to thank Dr. Anne Carey and Dr. Karen Royce for their support, coordination, and academic guidance with keeping my coursework, academic goals and research on track throughout my undergraduate experience. I also want to greatly thank Dr. Michael Barton for his support through a difficult time during my undergraduate studies. I would not be graduating right now if it were not for Dr. Barton. I want to thank Brent Curtiss, Jess Hillman and Daniel Dunlap for their IT help with my laptop and program issues, I would have been completely stuck on this thesis without them. I want to thank Dr. Ralph von Frese, who started me on my path with research when I first came to Ohio State and was patient with me guiding me through my first research project. I also want to thank Dr. Dave Miller, who started my interest in geology in the first place when I attended Clark State. I also want to recognize Dr. Lawrence Krissek, who during another difficult time with my mother's passing was extremely understanding, supportive, and went above and beyond to make sure that I could complete my studies with his class. He put in extra time when he didn't have to, and I have greatly appreciated his effort. I also want to thank and recognize Jameson Scott for all of his support and advice through my undergraduate studies. I want to thank those individuals and organizations who have financially aided me since being at Ohio State; the Shell Undergraduate Research Experience (SURE), Ohio College Opportunity Grant, Federal Pell Grant, School of Earth Science Field Experience Travel Fund, Spieker Scholarship, Shipley Undergraduate Scholarship, Goldthwait Geology Fund, Federal Supplemental Educational Opportunity Grant, and the Presidents Affordability Grant. I also want to thank and recognize the Shell Exploration and Production Company for funding the SURE program.

I want to acknowledge the seismic data and the well logs that I used for my thesis was publically available for the ODP Leg 164.

I have to thank and recognize Jake R. Thompson, who was my biggest supporter throughout my time at Ohio State. Thank you for helping me with difficult coursework, your understanding and emotional support, easing my schedule, etc. For the numerous late night pick-ups from campus to weekend school work or moving us while I was away at field camp for the summer so that I could attain my degree. I would not be who I am and where I am today without him. I also want to recognize and thank my dad, Mark R. Mills, who strived to raise me to be driven, independent, set goals and aim high, and to be self-sufficient. He has made huge sacrifices for his family and has helped me when I've needed it. He has always been my number one supporter in life, and I'm proud to call him my dad: Thank you, love you pops. . I want to thank my family members such as my Aunt Kristie and Uncle Steve & Aunt Marla who has always kept me positive and encouraged me through college. I also want to thank my grandparents Linda and Morgan Mills for all of the love and support you've given over the years with every care package to every holiday celebrated to every long distance phone call for my birthday. It's not easy being so far away, but you made it work. I appreciate all of you so much and love you dearly. I also want to thank Maria Thompson, Naomi Adaniya, Sarah Munson, Mike Angle, Jim McDonald, Tim Leftwich, Mike Hansen, Dee Caudill, Theresa Colson-Mooney, and Stephanie Sherman for their kindness, guidance and support. Lastly, I want to thank all of those individuals that I have met or haven't met that influenced my journey. To those individuals who work hard trying to get the best opportunities to the students, those classmates and friends that helped me get through the day, and the family and friends that supported me; Thank you.

## LIST OF FIGURES

Figure 1	Photograph of a Gas Hydrate	p.16
Figure 2	Location Map of Seismic Area	p.16
Figure 3	Example of BSR in Seismic Data	p.17
Figure 4	Location Map of the Wells	p.17
Figure 5	Map of the Seafloor	p.18
Figure 6	Map of the BSR	p.19
Figure 7	Map of the Isopach	p.20
Figure 8	A-A'	p.21
Figure 9	B-B'	p.22
Figure 10	A-A' & B-B' Zoom on Seafloor and BSR	p.23
Figure 11	Well Log Data for Site 994	p.24
Figure 12	Well Log Data for Site 995	p.25
Figure 13	Well Log Data for Site 997	p.26
Figure 14	Line R7 from Hornbach	p.27
Figure 15	Map of the Seafloor (VuPAK)	p.28
Figure 16	Map of the BSR (VuPAK)	p.28

## **INTRODUCTION**

### **HYDRATES**

Gas hydrates are an ice-like substance with a crystalline structure consisting of interlocking water molecules surrounding a gas molecule that form when the pore space is saturated in a delicate zone of low temperatures and high pressure within the Arctic permafrost or ocean sediments (Taylor et al., 2000). According to Beaudoin et al. (2014b), gas hydrates may have the potential to be a new global energy resource, expecting the amount of hydrate to be greater than all of our current mainstream energy resources combined. There is still much research to be done to narrow the mechanics, properties, and conditions in which these hydrates form, as some challenges include developing the technology to safely extract the hydrate (King, 2015).

Methane hydrates are a gas hydrate in which the water molecules are surrounding a concentrated methane molecule. Hydrates are considered to be a fairly clean burning fuel and methane is the most common kind of gas hydrate, accounting for roughly a third of the world's mobile organic carbon (Beaudoin et al., 2014a). These methane hydrates form in low temperature and high pressure and must stay within those conditions to remain stable, otherwise becoming unstable and transforming back to gas and water (U.S. Department of Energy, 2015b). These hydrates are highly concentrated. According to the U.S. Department of Energy (2015a), if you melt one cubic meter of methane hydrate, it releases 164 cubic meters of methane gas. At room temperature and pressure, gas bubbles can exsolve from gas hydrates, as shown by Paull and Matsumoto (1998) (Figure 1).

Scientists have been researching the mechanics and environments that harbor this potential energy giant, along with conducting estimates to quantify this resource (Beaudoin et al., 2014a). With the projected amount of methane hydrate that have been estimated worldwide, it is possible that it may exceed the combined energy contents of all other fossil fuels (Beaudoin et al., 2014b). Although methane hydrates could potentially exceed other combined energies, the amount of methane hydrate



is unconfirmed and has a wide range of distribution (Beaudoin et al., 2014b). More recent estimates suggest that original estimates of global carbon inventory in methane hydrate may be only one quarter of the early estimates (Hornbach et al., 2008).

Different ways to refine the estimates include using more advanced methods. These methods include 3D seismic of the region and large scale drilling analysis where free-gas concentrations are sampled and directly detected (Hornbach et al., 2008). By combining these two methods, we can hope to better quantify the methane hydrate in the region (Hornbach et al., 2008). Currently, there are several countries that have developed national gas hydrate research programs, with both industry and academia helping to accelerate discoveries and our understanding of gas hydrates (Beaudoin et al., 2014b). As of today, there is no large-scale commercial production, as it is still in the research/experimental phase being conducted by the United States, Canada, Japan, and India (King, 2015).

## **SIGNIFICANCE OF HYDRATES IN ENERGY, CLIMATE AND GEOHAZARDS**

Methane hydrates have been thought to be a potential link to past global warming events and to increased carbon levels in the atmosphere (Gaskill, 2004). Potential geological and environmental issues linked to methane hydrates are possible slumping events due to slope instability, underwater landslides, or subsidence during attempts to extract the hydrate (King, 2015). This is a concern because methane is a very potent greenhouse gas and releases of any large amount of methane into our atmosphere could potentially elevate global temperatures (King, 2015). If such an episode were to occur, escaping methane could dissolve into the water and be emitted into the atmosphere, where it will oxidize over time. This can raise the temperatures and subsequently cause melting of more methane hydrates. More melting of the subsurface hydrates would be likely to occur because the stability zone where the hydrates form are based on a delicate balance between low temperature and high pressure, and with the temperatures rising it will alter the depth at which these low temperatures keep the hydrate stable.

Although this issue has been presented as a potential catastrophe, USGS research has deduced that a catastrophic melting episode sending large amounts of methane into the atmosphere is improbable (King, 2015). Sedimentation and erosion can cause fluctuations in the temperature and pressure within the stability zone. As sedimentation occurs, it increases the temperature and pressures; as erosion occurs, temperatures cool and pressures decrease (Hornbach et al., 2008). Any kind of change in temperature or pressure within the stability zone can cause the area to become unstable and result in the structure failing and releasing methane in an unknown way and an unknown amount.

## **THE GEOLOGIC SETTING OF THE BLAKE RIDGE REGION**

“Previous studies indicate that Blake Ridge, with its generally homogenous stratigraphy, simple geologic structure, and limited geophysical variability represents an ideal natural laboratory to isolate and study gas hydrate” (Hornbach et al., p.5, 2008). The data used for this thesis were collected on the research vessel *Maurice Ewing* operated by the Lamont-Doherty Earth Observatory of Columbia University during the fall of 2000 (Hornbach et al., 2008). Figure 2 illustrates the location of the area in which seismic data were collected in relation to the east coast of the United States. This area is known as Blake Ridge. The study area of approximately 45 km in length and 7.5 km in width, covering roughly 370 square kilometers, is located 515 kilometers east of Savannah, Georgia. Blake Ridge is one of the largest methane hydrate provinces in a passive margin on Earth and has been heavily studied for such reason (Hornbach et al., 2008). Blake Ridge provides an ideal location because the dynamic system has a relatively simple tectonic setting and uniform lithologies. As research is further conducted, the gas hydrate system is noted to be much more dynamic than previously thought. Many aspects have been emphasized through research, such as the distribution and concentration of gas hydrates and free gas zones, the interaction between these hydrate reservoirs and the global carbon cycle, and the biological and symbiotic relationships to the area (Holbrook et al., 2008).

The bathymetry of the Blake Ridge region forms from a western driven undercurrent, eroding seafloor sediments from the eastern flank of the ridge and which are redeposited on the western half (Hornbach et al., 2008). To the north, the ridge crest is superimposed with sediment waves that are asymmetrical, southwest-oriented, and eroded perpendicular to the undercurrent. This is unlike to the south, where the sediment waves take on an unusual shape most likely due to mixing of currents from the Gulf Stream and the undercurrent (Hornbach et al., 2008).

### **3D SEISMIC DATASETS AND WELL LOGS FROM ODP LEG 164**

There are two main parts to reading the seismic data; the sea floor and the bottom-simulating reflector (BSR). The BSR represents the methane hydrate/free gas phase boundary, typically running subparallel to the seafloor. Above the phase boundary pressures can be too low and below this phase boundary the temperatures and pressures are too high for hydrate to remain stable. Figure 3 is the BSR in seismic data in the summary written by Paull and Matsumoto (1998), where they identified the BSR. The strong lines defined as the BSR distinguish the base of the methane hydrate stability zone. Through seismic studies, the BSR appears to be patchy or absent below the sediment wavefield and below the eastern erosional flank where eroded sediment waves extend below the hydrate stability zone (Hornbach et al., 2008). In contrast, seismic studies report a distinct BSR where there is an absence of sediment waves below a majority of the crest of Blake Ridge (Hornbach et al., 2008). There are two hypotheses as to why the western half has more hydrate underneath it than the eastern half with great belief of its connectivity to sediment waves and erosion from scientists Dillon et al. (1998) and Holbrook et al. (2002) as discussed by Hornbach et al. (2008). The discontinuous BSR on the eastern half occurs “where eroded sediment waves extend below the hydrate stability zone” (Hornbach et al., p. 2, 2008), result is also generally seen. So in other words, where erosion has occurred, less gas is present.

Dillon et al. (1998) and Holbrook et al. (2002) have different hypotheses for a lower gas presence underneath the sediment waves in the seismic data. In discussing Dillon et al. (1998), Hornbach et al. said Dillon et al. (1998) propose “the sediment waves are normal faults, representing a seafloor collapse

triggered by catastrophic gas escape” (Hornbach et al., p.2, 2008). Holbrook et al. (2002) later suggest that what others believed to be faults were actually eroded sediment waves, suggesting the area has a substantial amount of escaping gas (Hornbach et al., 2008). The two different hypotheses propose that there is evidence of substantial quantities of methane released in this region, which could cause the BSR to be patchy on the eastern half (Hornbach et al., 2008). Neither Dillon et al. (1998) nor Holbrook’s et al. (2002) hypotheses address direct evidence for ongoing or recent fluid flow below sediment waves (Hornbach et al., 2008). As Holbrook et al. (2002) show through 3-D seismic data, the buried sediment waves appear to be of sedimentary origin and not as normal faults proposed by Dillon et al. (1998). The 3-D seismic data show that the buried sediment waves on the eastern flank trend northwest to southeast similar to the crest of the ridge (Hornbach et al., 2008). The buried sediment waves extend farther beyond the seafloor bathymetric data suggested from Hornbach’s study, but they appear to have smoothed out over 6 Ma due to seafloor erosion, masking the seafloor expression (Hornbach et al., 2008).

Core was analyzed from three ODP Leg 164 well sites; Site 994, Site 995, and Site 997 (Paull and Matsumoto, 1998). Figure 4 provides the locations of each of the ODP well sites in relation to the east coast of the U.S. Coring results from these three well sites “reveal near-uniform fine-grained silt and mudstones to depths of 700 mbsf (meters below seafloor) and both coring and seismic data indicate that these sedimentary conditions exist across the study area” (Hornbach et al., p.2, 2008). How much hydrate is within the pore space is vital to evaluate hydrate distribution which will help establish more accurate maps of the subsurface within the area. With more hydrate within the pore space, the p-wave velocity will increase, changing the subsurface appearance within the seismic data. Beaudoin et al. (2014b) stated that although it is assumed that as the pore space is replaced with solids, the p-wave velocity should increase; however, the extent of the increase in p-wave velocity is unknown because the hydrate distribution within the pore space of the sediments are not yet established.

There are two different logs I used from ODP Site 994, Site 995, and Site 997: gamma ray logs and the resistivity logs (which can also be referred to as the dual induction logs). The gamma ray logs tell what kind of lithology exists with depth, while the resistivity logs tell the fluid type present from the level of resistance or conductivity from electrical current. Gamma ray logs measure the radioactivity being emitted from each sediment layer. In these environments, gamma ray logs are measuring how much is being emitted in each formation with the spikes to the right (indicating more abundant natural gamma ray) and the spikes to the left (indicating less abundance of natural gamma ray) in reference to the vertical black line through the middle of the log. For example with sand, clay, and shale, the gamma ray would spike to the left if it is sand-rich and to the right if it is clay-rich or shale. The resistivity logs measure how resistant or conductive the fluid is within the pore space. So the resistivity log would indicate whether the fluids are fresh water, salt water, oil, gas or hydrate, etc. For this thesis, I correlated the gamma ray and resistivity logs to determine where the BSR may lie in each well when the gamma ray gradually increases to the right and the resistivity spikes to the right. I determined the location of the BSR at Site 994 at ~450 meters using the gamma ray log shifting to the right (Figure 11). Sites 995 and 997 (Figures 12 and 13) determined more by the resistivity logs, with both spiking to the right at 425-450 meters.

## **METHODOLOGY**

### **MAPPING HYDRATES**

Because the seafloor should have a positive coefficient reflection and this dataset has reversed polarity, the seafloor should be the uppermost horizon with a strong negative reflection coefficient. Mapping the BSR by following the current concepts that are accepted in identifying the BSR in seismic data, the BSR is indicated by the strongest positive reflection coefficient at depth below the seafloor running subparallel to the seafloor. Layers that contain trapped free gas often generate strong reflections (i.e. bright spots) because low velocities are generally associated with free gas (Taylor et al., 2000). Reflection-strength anomalies correlate well with regions of active faulting visible in the data. Therefore, it is likely that the sub-vertical faults contain gas and are acting as fluid conduits (Taylor et al., 2000). An

analysis of the BSR shows that the BSR has two different halves in this area. The western half has a solid, continuous horizon with simple bedding and the eastern half with a discontinuous BSR horizon. The complicated nature of the eastern half of the study area precluded a thorough analysis for this thesis. There was also a time constraint involved, so for this thesis I mapped only the continuous half on the western side.

In my dataset, I chose a grayscale color bar to illustrate the impedance contrast, with white representing negative impedance contrast and black representing the positive impedance contrast. Plots of points along a constant impedance reflection created a horizon, or a digital layer within the seismic data. When pieced together, this created a three-dimensional map. After I mapped the seafloor and the BSR, I looked for any geological issues or outliers in VuPAK. VuPAK is a 3-dimensional geological interpretation module within IHS Kingdom suite. The seafloor horizon that I created in VuPAK allowed me to view the seafloor in three dimensions using the x-coordinates (x-axis), y-coordinates (y-axis), and two-way time (z-axis) (Figure 15). The BSR was mapped within the entire seismic area, but I only proceeded with the western half of the BSR (Figure 16).

I created two cross sections (Figure 8 and Figure 9) trending southwest to northeast, running with the length of the seismic array. These cross sections both extend about 45 kilometers, the same length as the dataset. Each cross section is meant to display a series of geological features such as faulting, folding, evidence of salt domes, and underwater landslides. Choice of two horizons that are best representative of the different sections of the area gives a sense of what is happening with the geology in the northern part of this area versus the southern.

With the Logging Database from ODP's Janus Web Database, I was able to retrieve the gamma ray log data and the resistivity log data from each of the ODP Well Sites; Site 994, Site 995, and Site 997. Hydrates are generally expected to have low gamma ray values and high resistivity (Majumder, 2009), so observation of the gamma ray logs and the resistivity logs will show if there is hydrate present and at

what depth it can be located within the well. The data were retrieved from the Janus Database and imported into Microsoft Excel. In Excel, I was able to create a side-by-side scatterplot for both gamma ray and resistivity for each ODP site. This made it easier to compare the logs not only between the two logs for each site, but easier to compare each site as well.

After exporting the maps of the seafloor, the BSR, and the isopach out of IHS Kingdom Suite, I imported all three into ArcGIS. ArcGIS is a geographic information system (GIS) capable of working with and creating maps. This program allowed me to create the contours, add hillshade for a more three-dimensional effect, and to create essential parts of the map. I then exported the maps from ArcGIS and imported the scatterplots and all three maps into Adobe Illustrator.

## **RESULTS**

### **3D MAPPING OF HYDRATE SYSTEM OF BLAKE RIDGE**

The maps of the seafloor and the western continuous BSR shared a common bathymetric pattern that gradually deepens, with the shallowest point lying in the northwest and the deepest point towards to east. The isopach map differed from the bathymetry pattern, varying more in thickness where it is thinnest. The seafloor was relatively easy to map throughout the area because the interface between the seawater column and the seafloor appears as a bright, strong reflection. The BSR was easier to map in the western half because of its simple bedding and more apparent, subparallel reflections to the seafloor. All of the maps that I created are paired with a location map of the seismic area, the location of the wells in relation to the seismic area, and the cross section lines A-A' and B-B' that I created in relation to the seismic area. The seafloor is 45 kilometers (30 miles) in length, covering roughly 300 square kilometers (116 square miles)(Figure 5). My interpreted seafloor has a range of depth. The seafloor ranges from 2005 meters (6578 feet) to 2618 meters (8592 feet) from West to East. The depth was calculated using the two-way time (TWT) and a seawater velocity of 1550 meters per second. TWT is the time measured from leaving the source and bouncing back to the receiver. The map of the BSR (Figure 6) is represented in the same manner as Figure 5, except the depth is in time (TWT) instead of meters and the BSR was mapped in the continuous western half instead of completely across the study area like the seafloor map. The continuous western BSR appeared at its most shallow point at 3.03

seconds in 'TWT' and the deepest appearing around 3.34 seconds in 'TWT'. The continuous BSR extended from 21 kilometers to 25.3 kilometers from the western most edge of this seismic area. With 1700 meters per second for the velocity through the hydrate zone, the BSR is placed at 2573 meters to 2836 meters. Figure 7 displays the isopach map created by measuring the thickness between the seafloor and the interpreted BSR in terms of seconds ('TWT'). With 1700 meters per second for the velocity and the calculated the isopach map, the thickness between the two horizons ranged from 322 meters to 455 meters, with the thickest portion in the northwest and the thinnest portion in the east. As far as the two cross sections I displayed as Line A-A' and B-B', I chose two lines 3.5 km apart from one another in order for the cross section to appear best representative of the differences in the subsurface of the seismic area.

## **DISCUSSION**

The maps I created were consistent with previous maps of the area. Hornbach et al. (2008) provided their bathymetric map of Blake Ridge, which also included a portion of the sediment wavefield to the northwest of the study area. Hornbach's bathymetric map also illustrated that the sediment waves became less prominent as you moved further towards the east of the seismic study area where it illustrates the pathway of the Western Boundary Under-current (WBUC). This would explain why my bathymetry decreased from the west to the east, because of the WBUC and the drop off of the continental shelf towards the abyssal plain. The seafloor depths in Hornbach et al. (2008) had the shallowest depth at approximately 2600 meters and the deepest section at 3200 meters. These values are much greater by 600 meters than the values that I calculated. However the range between the shallow and the deep ends of the seismic area are the same at approximately 600 meters with the same bathymetry. The reasons for these differences are unknown.

The seismic area studied by Hornbach et al. (2008) was ~370 square kilometers in size, while my measurements through Kingdom for my mapped seismic area was ~300 square kilometers. So my calculated area through IHS Kingdom Suite was a fraction smaller, by ~19%. The isopach I created represents the thickness between the seafloor and the interpreted BSR. The only isopach mentioned by



Hornbach et al. (2008) referred to correlating past dated seafloors to evaluate sedimentation rates. So I created an isopach map and Hornbach created an isopach map, but they calculate the thickness between two different sets of horizons.

Having worked with the acoustic impedances from the seismic data, it is important to note what that means to have a contrast in impedances. The white section of the color bar represents the strongest possible reflections, the black the weakest reflections and with different shades of gray as the in-betweens but still representing positive or negative. The reflection strength or brightness depends on the seismic impedance, which is the product of p-wave velocity and bulk density. Any change in p-wave velocity or bulk density will affect the brightness of the impedance contrast, but the impedance contrast is also affected by porosity. Bulk density is inversely related to the porosity; meaning generally the higher the porosity, the lower the bulk density and the lower the porosity, the higher the bulk density. The BSR depth is not only based on a delicate balance of pressure and temperature as stated earlier in the thesis, but also on sedimentation and erosion, with sedimentation lowering temperatures and erosion shifting the depth of the BSR to a new lower depth, respectively (Hornbach et al., 2008).

Hornbach et al. (2008) described the bathymetry and processes that are occurring in the western half and the eastern half of the seismic area, as the western half is constantly undergoing sedimentation and erosion, while the eastern half experiences higher rates of erosion causing the BSR to appear patchy or intermittent. This could explain why the western half displays a stronger BSR due to sedimentation and erosion creating a more stable area than compared to the eastern half which appears intermittent because of the constant erosion from the westward bound under-current eroding the east and depositing in the west explained by Hornbach et al. (2008). My assumption was the stability zone is constantly shifting and not allowing enough time for a solid continuous horizon to form. Moderate sedimentation and erosion occurring in this area tell us that there is a dynamic hydrate system present (Hornbach et al., 2008). The BSR needs a balance among temperature, pressure and salinity, but it is

largely dependent on temperature and less dependent on pressure and salinity (Hornbach et al., 2008). Temperature is the most sensitive factor for this delicate balance. A greater sedimentation rate will lower the temperature at a given depth below the seafloor resulting in the BSR rising. This is in contrast to the effect of erosion which deepens the BSR (Hornbach et al., 2008). Hornbach et al. (2008) stated that their BSR was found at depth from 3100 meters to 3300 meters, which was again 500 meters to 600 meters deeper than my calculations. The reason for this discrepancy is unknown. Hornbach et al. (2008) believed that the BSR extends over 50% of the seismic area, which was approximately what I found in my mapped BSR as well. The western BSR and the eastern BSR in my data appeared to match the appearance and description that Hornbach et al. (2008) also found through their study.

Within the study area, I created two cross sections to illustrate the bathymetric differences between the northern portion of the area and the southern portion, which are representative of the areas surrounding each cross section. Figure 8 illustrates the crossline A-A' created along Line 20 within the dataset for the northern part of the seismic area, providing a cross section at the top and an interpreted cross section of A-A' at the bottom. On figure 8, it shows how the well locations correlate to the cross section perpendicular to the seismic area, to the interpreted seafloor and to the BSR. The BSR in A-A' does not quite follow the bathymetry of the seafloor, with the seafloor being more variant in depths within its horizon. You can also see this deformation within the immediate area located at the seafloor and just below the seafloor. This deformation could be due to submarine landslides, with the more famous ones particularly being the Cape Lookout Slide and the Cape Fear Landslide. Due to its location on a passive margin, submarine landslides should occur due to slope instability, with the failure likely occurring on slopes as low as 2°.

The stability zone within the subsurface appears to become more discontinuous as the seafloor shallows with depth just below where the seafloor appears to be very deformed. This deformation could be the result of sedimentation and erosion from currents in the area. The contrast in figure 8 is strongest just

below each of the horizons, which then becomes less distinct with increasing distance from each of the horizons. Below the BSR, the contrast becomes less distinct to almost absent to the eye with greater distance from the BSR. This could mean that below the BSR the contrast is low because the area at depth lacks differences in acoustic impedance. This could be due to the lithologies being less variable as they are above the BSR. So below the BSR, there may be one larger lithology or a lithology gradually dominating with depth. At this scale it is not possible to tell what it could possibly be from this seismic acquisition.

Figure 9 displays generally the same results with some subtle differences, however figure 9 represents Line 67, is in the southern part of the seismic area. The bathymetry of the seafloor represents a better example of how the BSR should be, running subparallel to the seafloor. This is because the seafloor appears to be more stable, and the seafloor contains more layers that are continuous. The contrast for figure 9 is the strongest for the seafloor and the BSR in B-B', which was much clearer and stronger than A-A'. There are many faults and folding within the subsurface of A-A', with a lot of them appearing above the BSR. The faults are much clearer, and the folding had lessened in B-B'. Knowing the types of faults and the locations of your faults is very important in industry. This will help in the industry deciding if there are any structural traps present. For example, a structural trap could be a fault acting as a trap, not allowing further migration and essentially sealing off the flow of the petroleum. This is especially important to determine prior to drilling so that time and money is not wasted on a dry hole. The Blake Ridge has quite a bit of fluid flow within the pore space. This fluid flow is a part of this bigger complex with it being a dynamic system.

Figure 10 displays the expanded portions along A-A' and B-B' represented in Figure 8 and Figure 9 by a vertical yellow rectangle. These expanded portions are provided to allow visual interpretation of what should be recognized as the seafloor and the BSR by using an application within IHS Kingdom Suite called Wiggle Trace, which displays the polarity of each impedance reflection to show if it is positive or

negative. Because the dataset had reversed polarity, the values appearing on the color bar to represent the impedance contrasts are opposite; the negative values representing a positive polarity and the positive values representing negative polarity. Typically the negative polarity is represented through Wiggle Trace by a blue fill to the left along the vertical line on the data, while the positive polarity is displayed with red fill to the right along the vertical line. Because the polarity is reversed, what Wiggle Trace is interpreting as positive and negative is actually the opposite; blue to the left is positive polarity and red to the right is negative polarity. A-A' and B-B' are along Lines, which in the data are the cross sections running southwest to northeast. With the Lines we also have Crosslines, which are shorter lines running perpendicular to the Lines from the northwest to the southeast with assigned numbers to each Crossline and Line helps for referencing. Hornbach et al. (2008) created a cross section that ran through the seismic area to correlate the subsurface between the seismic area and the ODP Well site 994, located approximately 10 kilometers south of the seismic area that just displays a cross section and the interpreted BSR, but anything representing polarity like IHS Kingdom Suite's Wiggle Trace is not present. So similarities are that both created cross sections, however they are demonstrating correlations among two separate aspects of the data in two different manners.

The log data analyzed in this thesis were the same log data that were analyzed in Hornbach et al.'s (2008) study. The logs that I worked with were ODP Leg 164 Site 994, Site 995 and Site 997 located approximately 10 kilometers south of the seismic area. Site 994 was the furthest from and Site 997 the closest to the seismic area. Figure 11, Figure 12 and Figure 13 illustrate the gamma ray logs and the resistivity logs collected for each site, representing the logs from the seafloor to depth with a BSR line through each log where the BSR might be expected to appear when the logs are applied to the seismic data. Previous drilling results from three of the ODP Leg 164 drill sites revealed near-uniform fine-grained silt and mudstones to depths of 700 mbsf (Hornbach et al., 2008). Coring and seismic data results indicated that these sedimentary conditions exist across the study area (Hornbach et al., 2008). Figure 14 allows visual correlation of the depth of the seafloor and the BSR at Site 994 compared to the depths of the seafloor and the BSR found within the seismic area. The BSR at and around Site 994

seems to run subparallel to the seafloor, as it should (Figure 14). The BSR on the north side starts at roughly 3200 meters below the sea surface and visually ends up around 3100 meters at the peak of the seafloor, then gradually decreasing back to roughly 3200 meters. This cross section provided by Hornbach et al. (2008) runs perpendicular to the two cross sections that I created as A-A' (Line 20) and B-B' (Line 67).

## **CONCLUSIONS**

My thesis was mapping key subsurface boundaries to determine the maximum thickness of methane hydrate within the hydrate stability zone contained in marine sediment. It consisted of creating three maps; the bathymetry of the seafloor, the bathymetry of the BSR, and an isopach map. These maps were created in a program called IHS Kingdom Suite, which is an analytical seismic and geophysical interpretation software provided by The Ohio State University. By mapping the seafloor and BSR horizons, I was able to calculate the thickness between the two horizons; thus creating an isopach map. Previous seismic studies have shown that the seafloor is normally characterized by a positive reflection coefficient/amplitude in seismic data, while the BSR is normally characterized by a negative reflection coefficient. In the case of the dataset I used for this thesis, the polarity is reversed, meaning that the seafloor appears having a negative reflection coefficient and the BSR appears to be positive.

I interpreted three-dimensional seismic data to map the two key subsurface boundaries for this study: the sea floor and the bottom simulating reflector (BSR). The BSR distinguishes the base of the methane hydrate stability zone, representing the phase boundary between solid methane hydrate and free gas where p-wave velocities decrease from a high velocity to a much lower velocity due to the free gas. I produced contoured structural and amplitude maps of each key boundary, including the seafloor, the BSR and the isopach map and created figures representing borehole data from sediment cores from three different wells (Site 994, Site 995, and Site 997). Figure 14 helps to correlate the depth of the seafloor and the BSR at Site 994 compared to the depths found within the seismic area. Even with the

bathymetry of the seafloor map I created being similar to past studies and the subparallel BSR being consistent with previous studies, the depths that I calculated for the BSR were 500–600 meters more shallow than that calculated by a previous study. I have shown that there are notable differences in the numbers that I have calculated compared to the numbers that Hornbach et al. (2008) calculated, and currently there are no reasons or explanations as to why the numbers calculated from Hornbach et al. (2008) and I are not the same.

There are a few environmental factors that have been discussed, such as not accelerating global warming by heating up the atmosphere from an accidental release of methane. Given that methane hydrates are potentially a global significant reservoir, mapping to establish correct depths, locations, saturation amounts, etc.: all of this is vital for quantifying the potential energy resource that may be extractable in the future.

## **SUGGESTIONS FOR FUTURE RESEARCH**

Future work could include a volumetric assessment of methane hydrates within this region. This could be achieved by applying existing algorithms from peer-review scientific literature. The results of the volumetric assessment based on the maps that I created could be compared to other past volumetric assessments to evaluate the assumptions, similarities, and differences. Someone could also run an analysis on the core data, trying to find a better correlation when outside of the seismic area. Other projects could include determination of concentrations of the methane present within the stability zone. Another project could include a determination of what the source is at depth creating the methane seeping upwards into the subsurface, mapping the entire BSR throughout the seismic area instead of just the continuous western half, etc. Future work could branch off this thesis could be by the dozens, and potentially applied elsewhere in hopes of establishing an updated, well-informed education on hydrates for academia and industry.

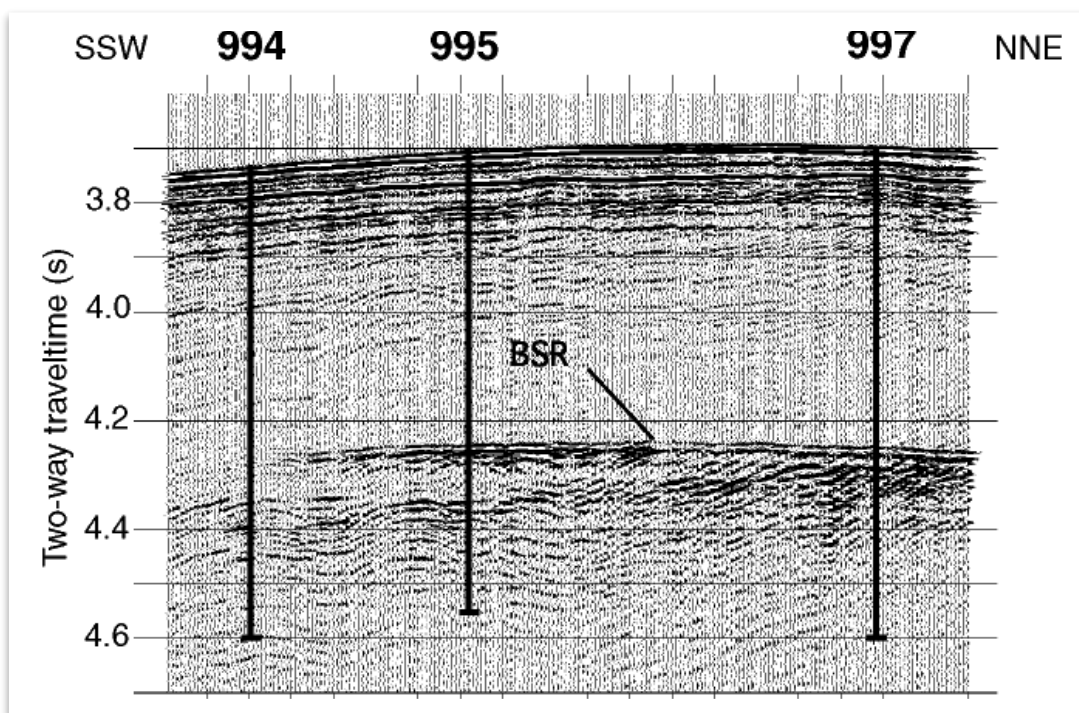
## FIGURES



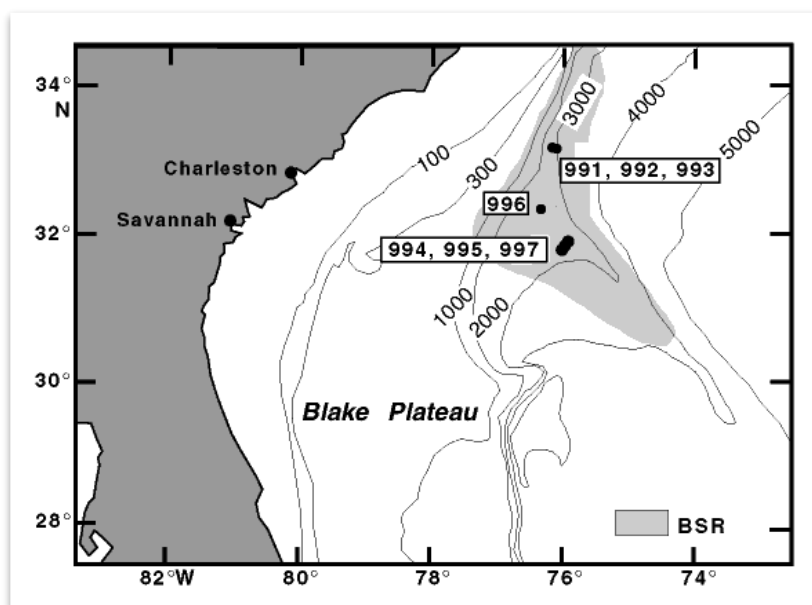
**Figure 1:** Photograph of a gas hydrate. Retrieved from (Paull and Matsumoto, 1998).



**Figure 2:** Location Map of dataset in the Blake Ridge Region. (Google Earth: [www.google.com/maps](http://www.google.com/maps))

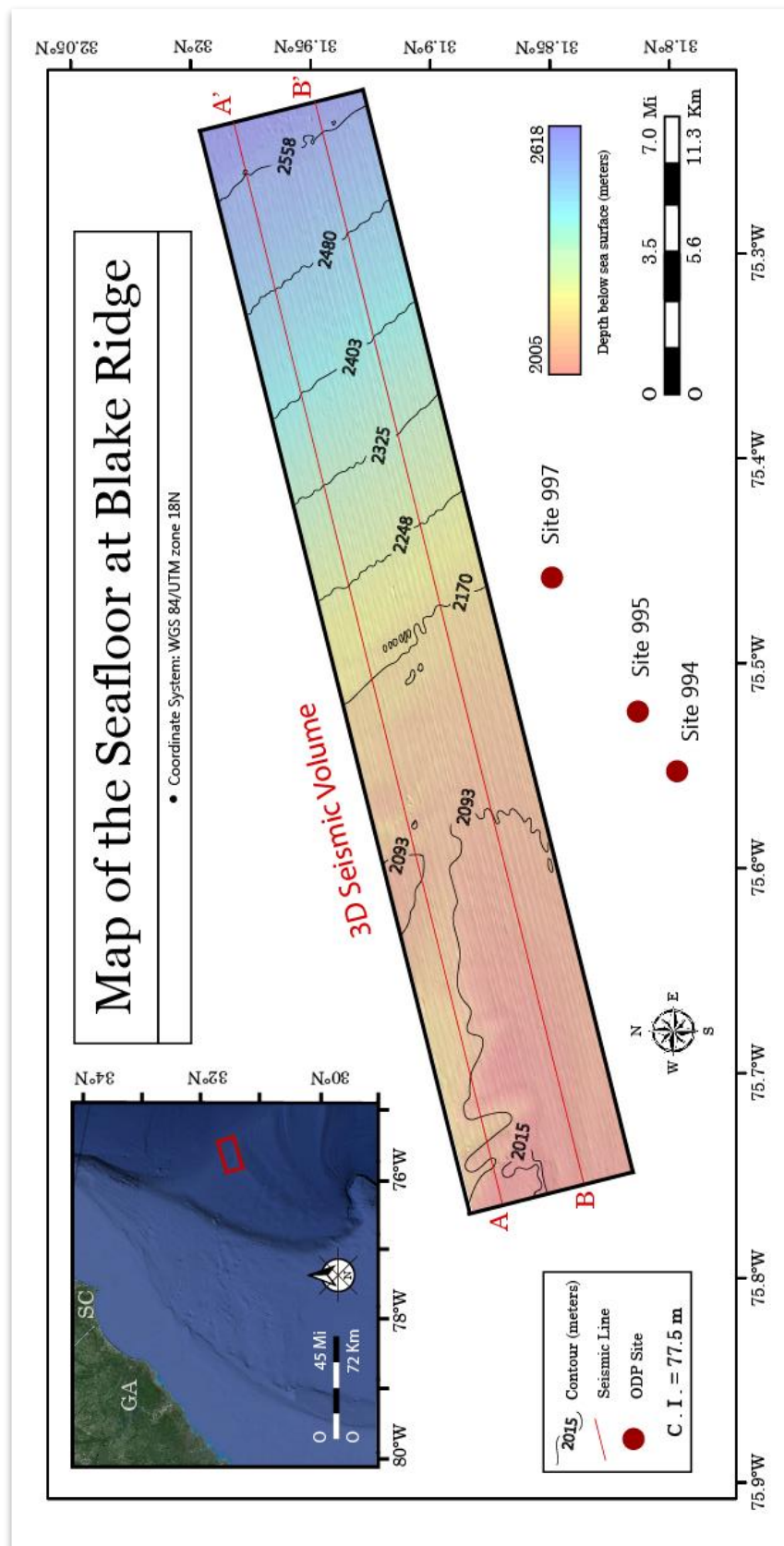


**Figure 3:** Example of BSR in seismic data. Retrieved from (Paull and Matsumoto, 1998).



**Figure 4:** Location map of the wells. (Paull and Matsumoto, 1998).





**Figure 5:** Map of the Seafloor in the Blake Ridge Region, Offshore North Carolina, U.S.A.

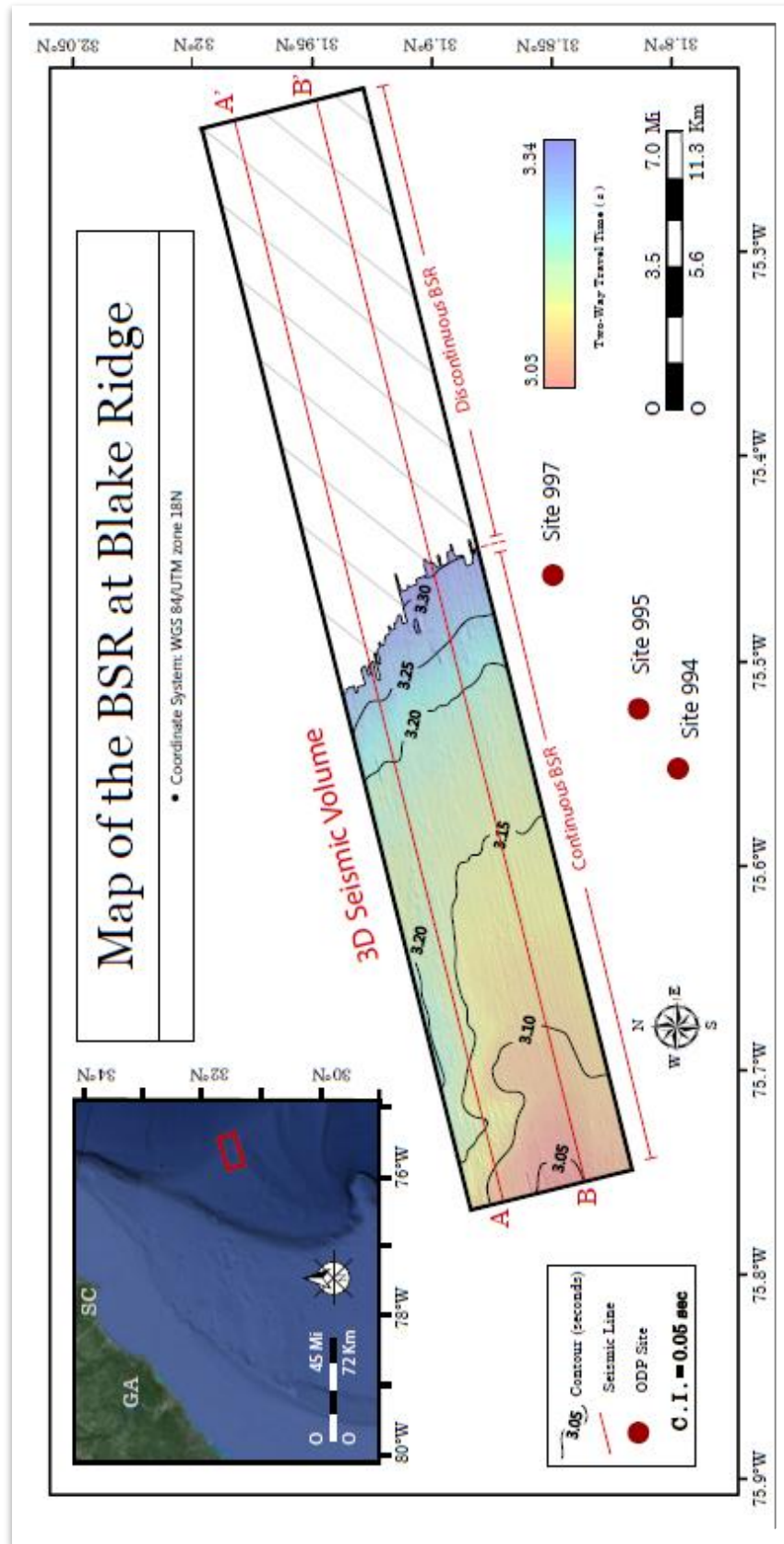


Figure 6: Map of the BSR in the Blake Ridge Region, Offshore North Carolina, U.S.A.

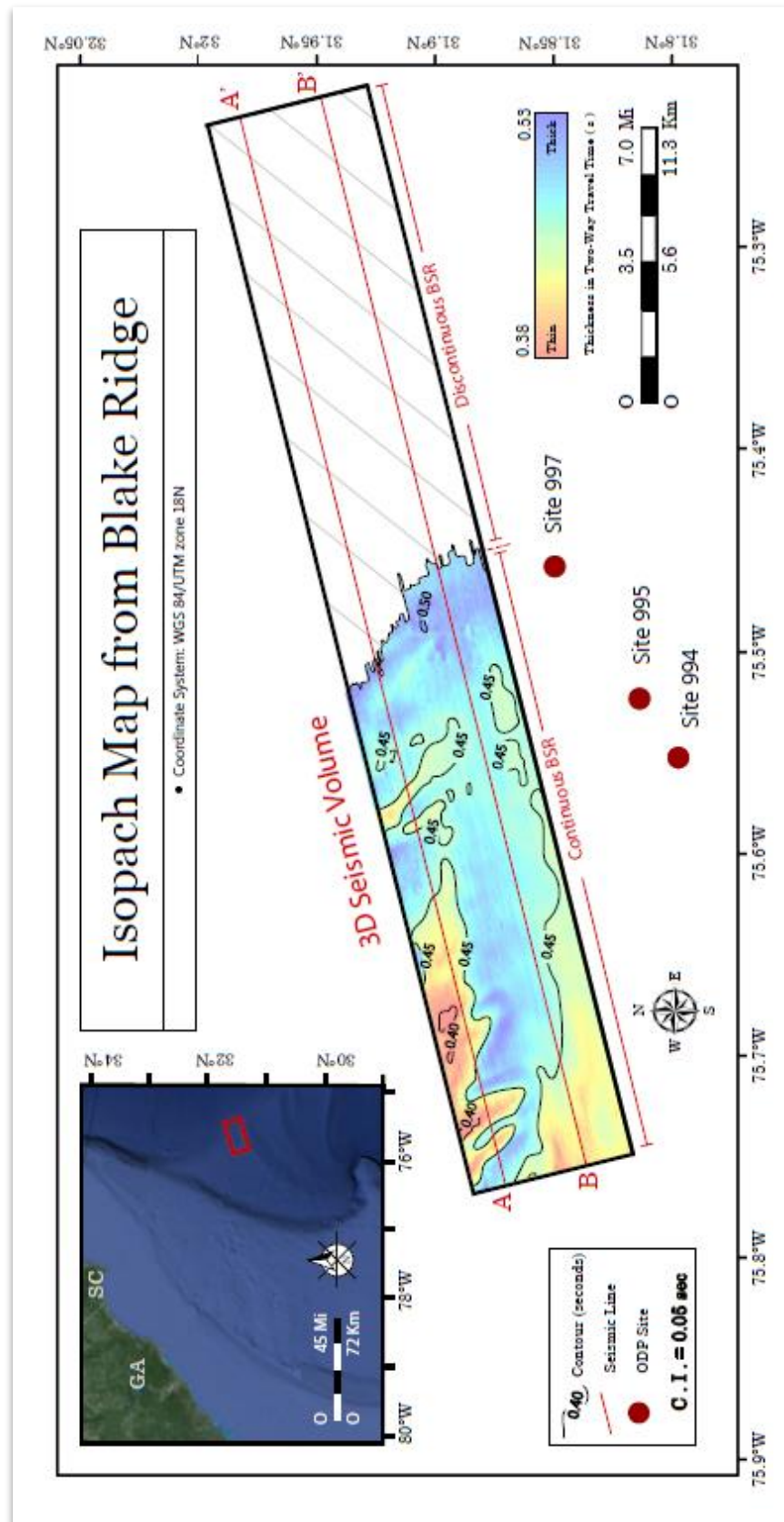


Figure 7: Isopach Map in the Blake Ridge Region, Offshore North Carolina, U.S.A.



# A-A': Line 20 from Blake Ridge Seismic Data

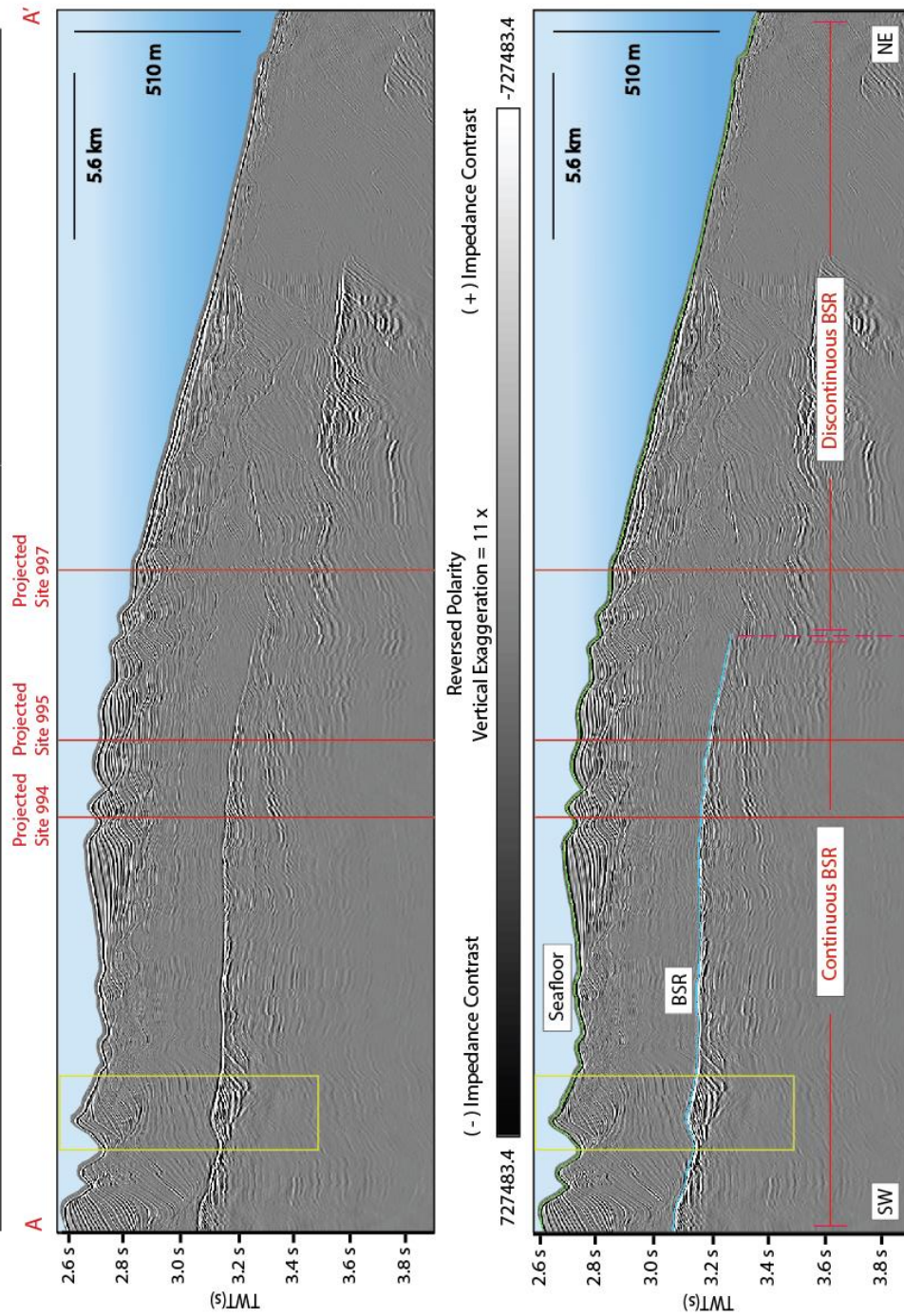


Figure 8: A-A' Cross Section.

# B-B': Line 67 from Blake Ridge Seismic Data

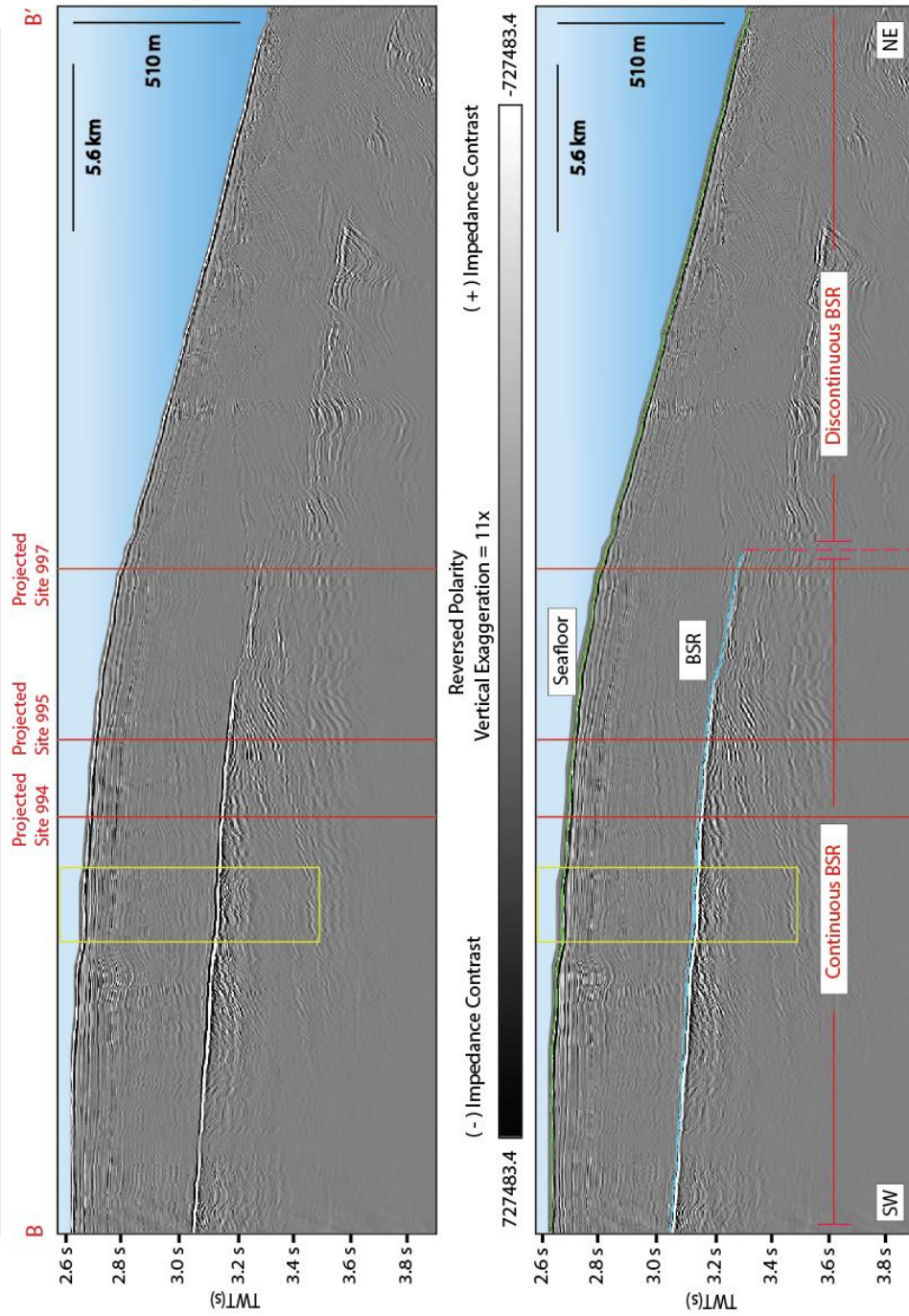


Figure 9: B-B' Cross Section.

## Line 20 and Line 67 with wiggle trace from Blake Ridge Seismic Data

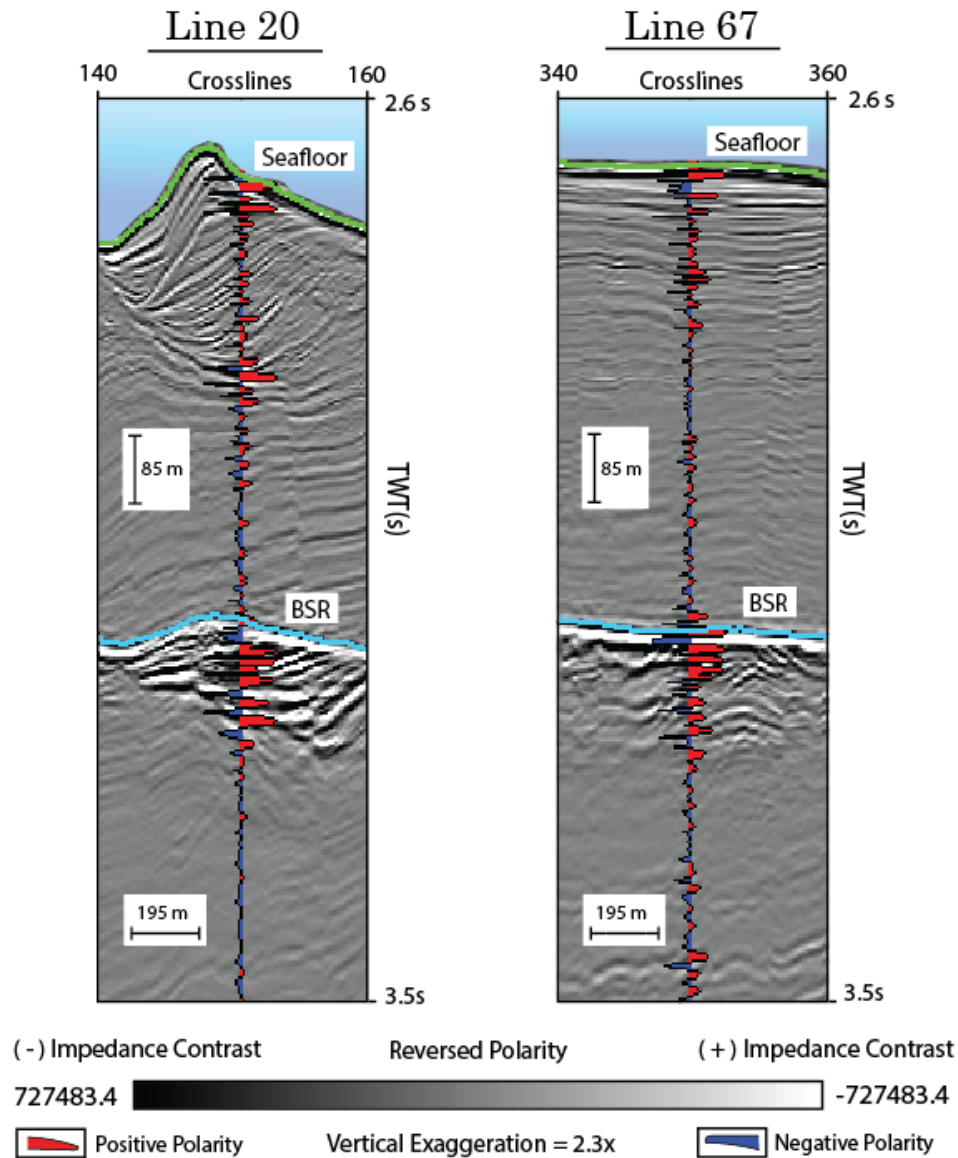


Figure 10: A-A' & B-B' Zoom into Cross Section for Seafloor and the BSR.

# ODP Leg 164: Site 994

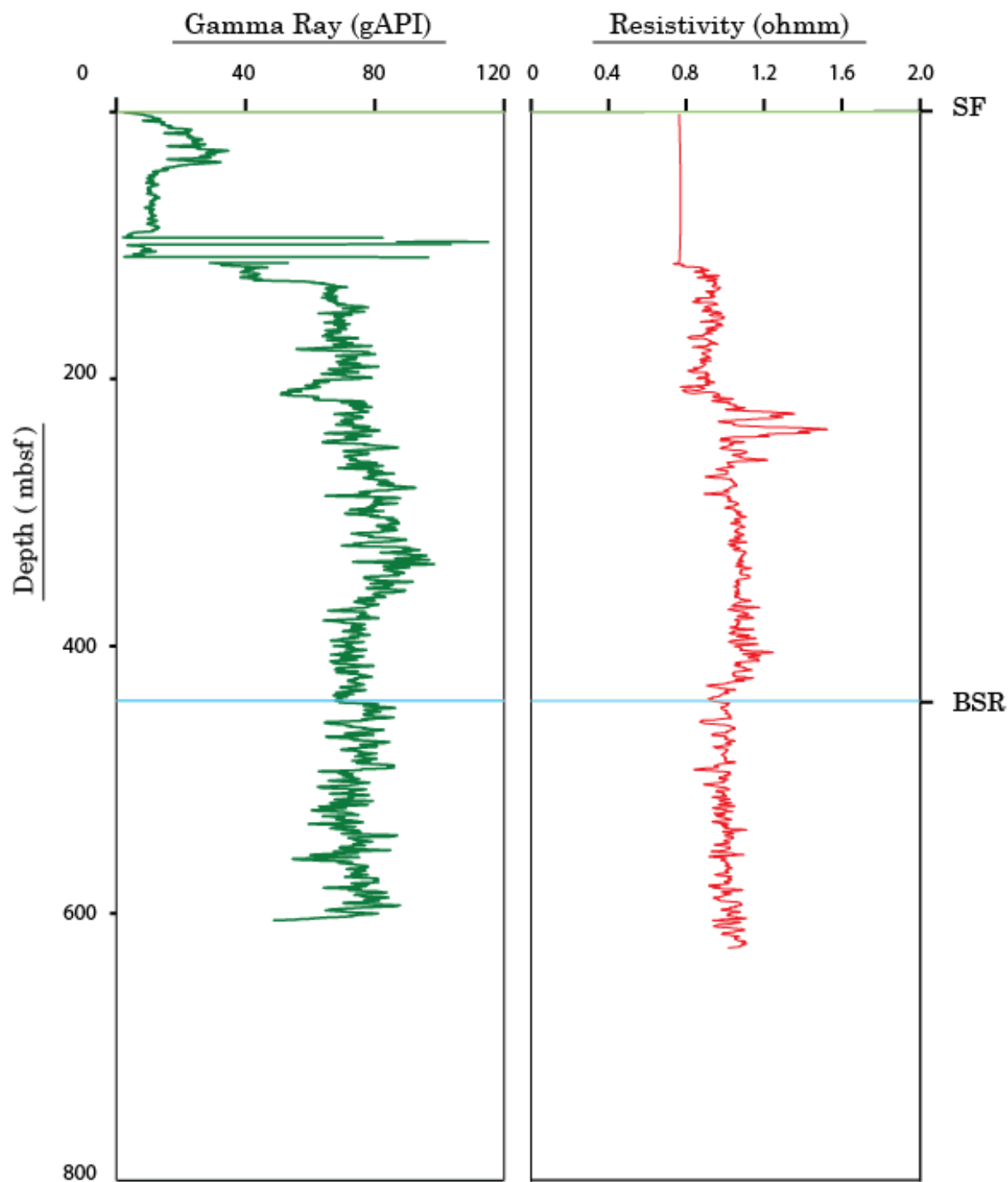


Figure 11: Well Site 994 Gamma Ray and Resistivity Logs

# ODP Leg 164: Site 995

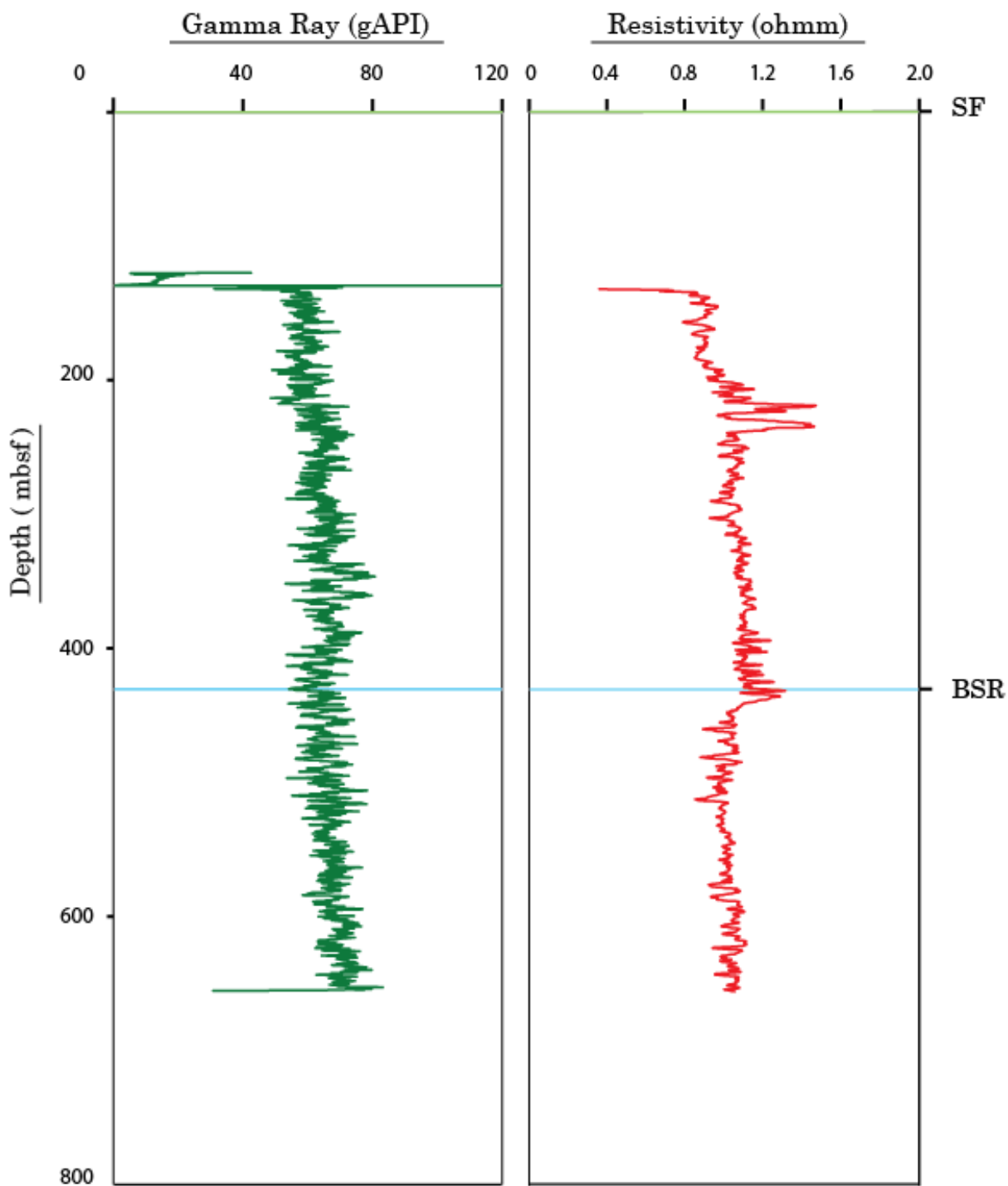


Figure 12: Well Site 995 Gamma Ray and Resistivity Logs



# ODP Leg 164: Site 997

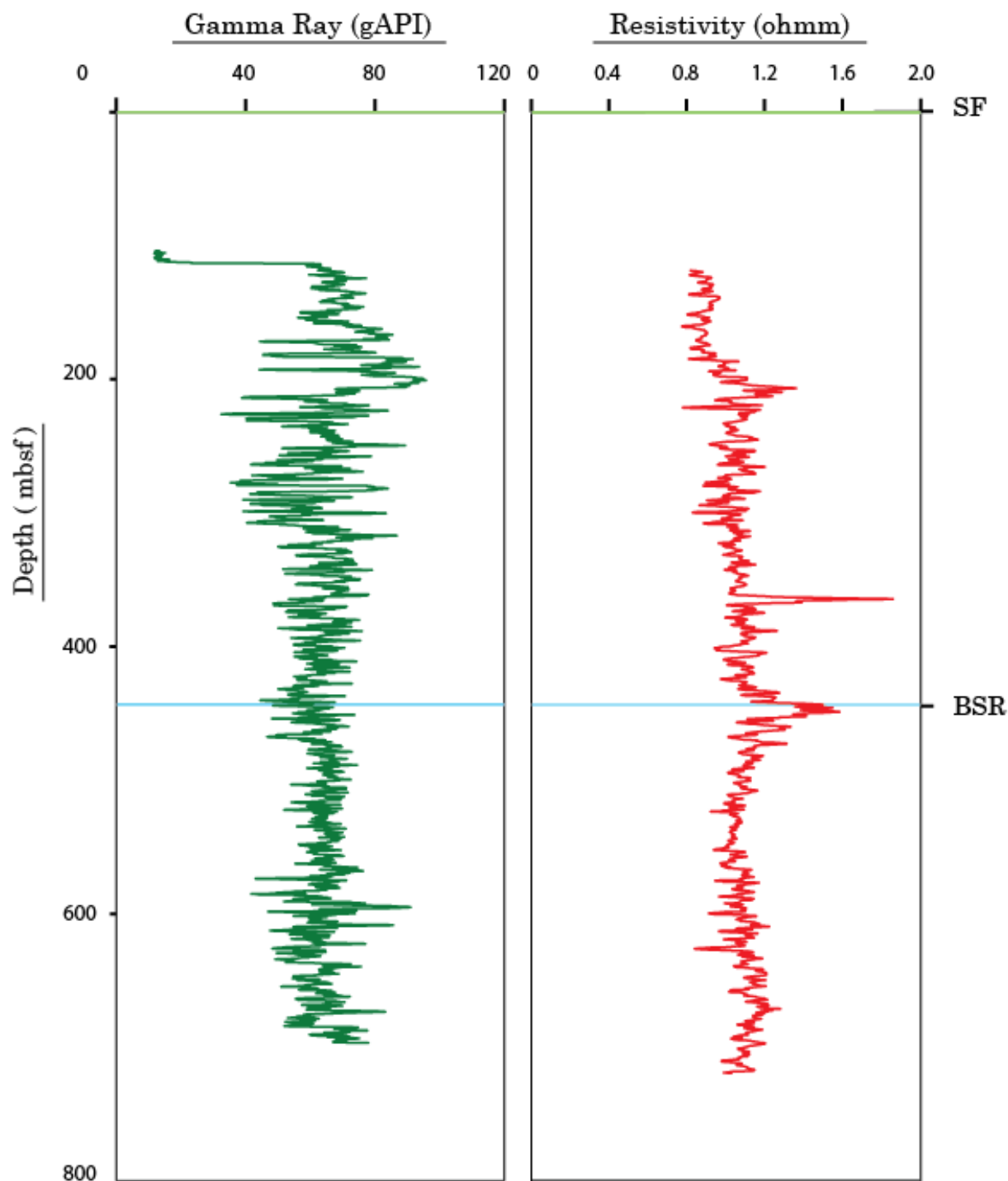
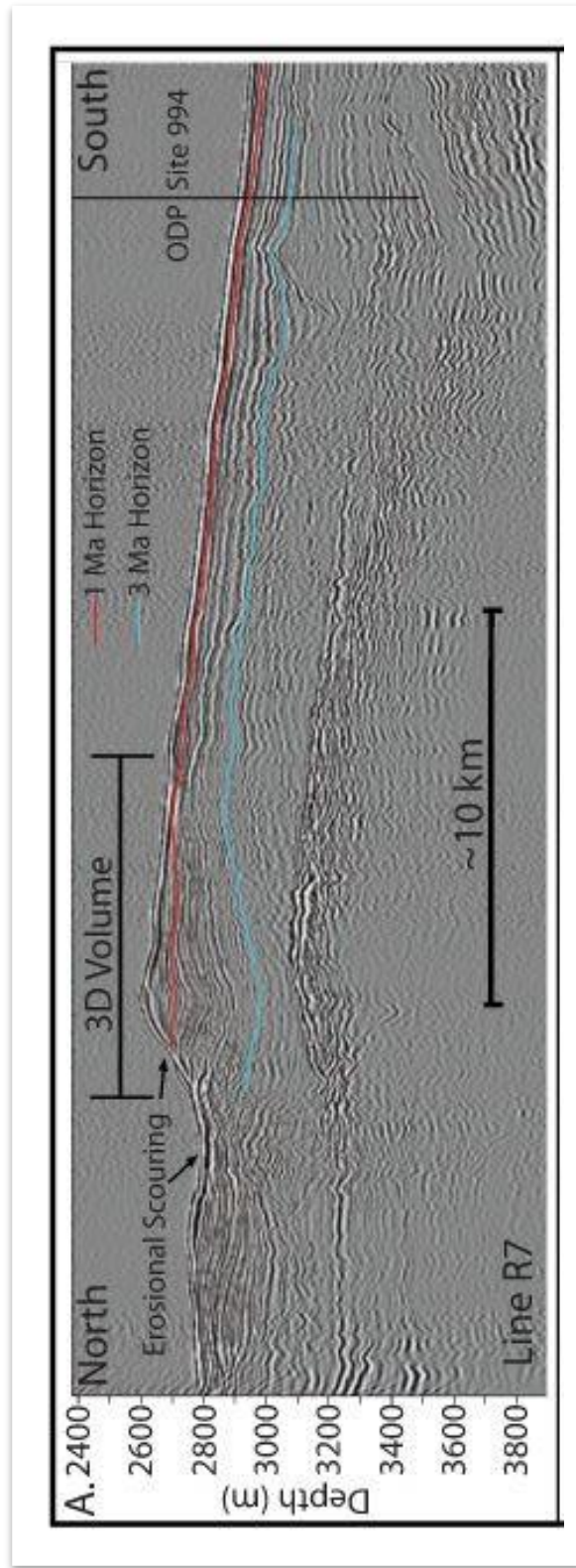
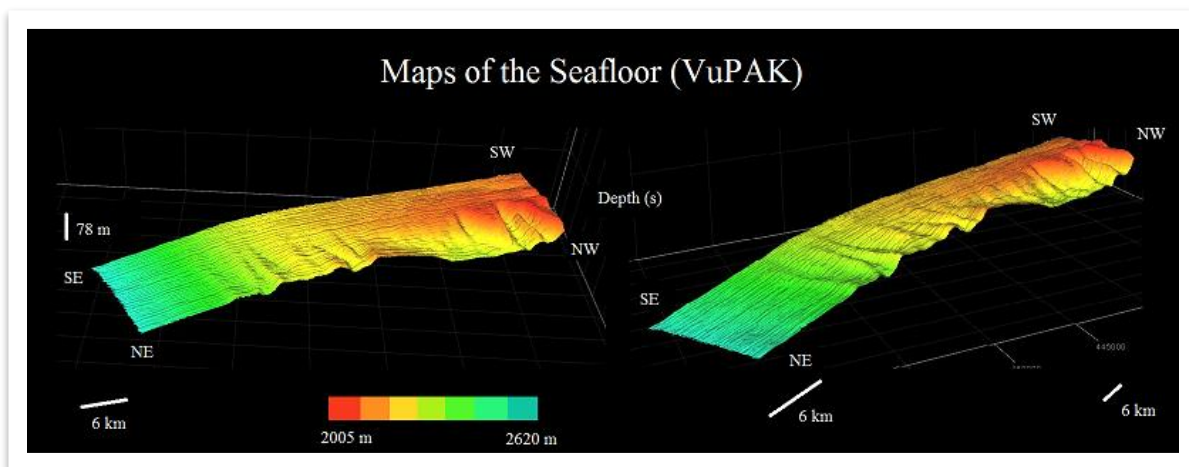


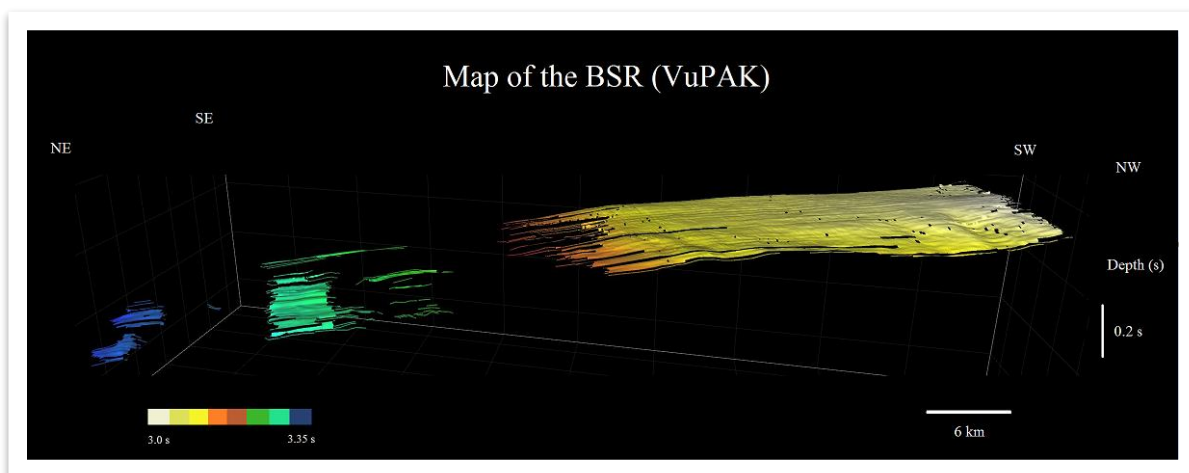
Figure 13: Well Site 997 Gamma Ray and Resistivity Logs



**Figure 14:** Line R7 illustrating the correlation between Site 994 to the seismic area. Hornbach, Saffer, Holbrook, Avendonk, and Gorman. (2008).



**Figure 15:** Map of the Seafloor (VuPAK).



**Figure 16:** Map of the BSR (VuPAK).

## REFERENCES CITED

- Beaudoin, Y.C., Dallimore, S.R., and Boswell, R. (eds), 2014a, Frozen Heat: A UNEP Global Outlook on Methane Gas Hydrates: Volume 1, United Nations Environment Programme: GRID-Arendal. Retrieved from <https://cld.bz/bookdata/CZ36dcr/basic-html/page-1.html>.
- Beaudoin, Y.C., Dallimore, S.R., and Boswell, R. (eds), 2014b, Frozen Heat: A UNEP Global Outlook on Methane Gas Hydrates: Volume 2, United Nations Environment Programme: GRID-Arendal. Retrieved from [https://sustainabledevelopment.un.org/content/documents/1993GasHydrates\\_Vol2\\_screen.pdf](https://sustainabledevelopment.un.org/content/documents/1993GasHydrates_Vol2_screen.pdf).
- Dillon, W.P., W. W. Danforth, D. R. Hutchinson, R. M. Drury, M. H. Taylor, and J. S. Booth (1998), Evidence for faulting related to dissociation of gas hydrate and release of methane off the southeastern United States, Geol. Soc. Spec. Publ., 137, 293-302.
- Gaskill, A, 2004, Catastrophic Methane Hydrate Release Mitigation, DOE Meeting Summary. Retrieved from <http://www.physics.rutgers.edu/~karin/140/articles/MethaneHydrates.pdf>.
- Holbrook, W. S., Hoskins, H., Wood, W. T., Stephen, R. A., & Lizarralde, D, 1996, Methane hydrate and free gas on the Blake Ridge from vertical seismic profiling, Science, v. 273, p. 5283.
- Holbrook, W.S., D. Lizarralde, I. A. Pecher, A. R. Gorman, K. L. Hackwith, M. Hornbach, and D. Saffer (2002), Escape of methane gas through sediment waves in a large methane hydrate province, Geology, 30(5), 467-470.
- Hornbach, M. J., Saffer, D. M., Holbrook, W. S., Van, A. H. J. A., & Gorman, A. R., 2008, Three-dimensional seismic imaging of the Blake Ridge methane hydrate province: Evidence for large, concentrated zones of gas hydrate and morphologically driven advection, Journal of Geophysical Research: Solid Earth, p. 113.
- King, H., 2015, Methane Hydrates, Geology.com: Oil and Gas. Retrieved from <http://geology.com/articles/methane-hydrates/>.
- Majumder, M., 2009, Identification of gas hydrates using well log data- A review, Geohorizons, p.40. Retrieved from <http://www.spgindia.org/geohorizon/july2009/mandira.pdf>.
- Paull C. and Matsumoto, R., 1998, Leg 164 Overview: ODP Publications. Retrieved from [http://www-odp.tamu.edu/publications/164\\_SR/chap\\_01/chap\\_01.htm](http://www-odp.tamu.edu/publications/164_SR/chap_01/chap_01.htm).
- Taylor, M. H., Dillon, W. P., & Pecher, I. A., 2000, Trapping and migration of methane associated with the gas hydrate stability zone at the Blake Ridge Diapir: new insights from seismic data, Marine Geology, v.164, no.1, p.79-89.

U.S. Department of Energy: Office of Fossil Energy, 2015a, Methane Hydrate. Retrieved from <http://energy.gov/fe/science-innovation/oil-gas-research/methane-hydrate>.

U.S. Department of Energy: Office of Fossil Energy, 2015b, Methane Hydrate Production Feasibility. Retrieved from <http://energy.gov/fe/methane-hydrate-production-feasibility>.